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Techno-Economic Analysis of a Stand-Alone Hybrid System: Application in Donoussa Island, Greece

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Abstract: Hybrid Renewable Energy Systems (HRES) are an attractive solution for the supply of electricity in remote areas like islands and communities where grid extension is difficult. Hybrid systems combine renewable energy sources with conventional units and battery storage in order to provide energy in an off-grid or on-grid system. The purpose of this study is to examine the techno-economical feasibility and viability of a hybrid system in Donoussa island, Greece, in different scenarios. A techno-economic analysis was conducted for a hybrid renewable energy system in three scenarios with different percentages of adoption rate (20%, 50% and 100%)and with different system configurations. Using HOMER Pro software the optimal system configuration between the feasible configurations of each scenario was selected, based on lowest Net Present Cost (NPC), minimum Excess Electricity percentage, and Levelized Cost of Energy (LCoE). The results obtained by the simulation could offer some operational references for a practical hybrid system in Donoussa island. The simulation results confirm the application of a hybrid system with 0% of Excess Electricity, reasonable NPC and LCoE and a decent amount of renewable integration.

Keywords: stand-alone hybrid system; HOMER Pro; simulation-optimization; techno-economic analysis; excess electricity percentage; Net Present Cost (NPC); Levelizez Cost of Energy (LCoE)

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1. Introduction

Electricity power is vital for people's daily life, social and economic development during the centuries. Power systems typically include four components, that correspond to the four main issues, namely generation, transmission, voltage transformation, and consumption. In some remote areas like islands, villages and farms it is difficult to construct transmission and distribution system for such a small demand of electricity. As a result, there are people all over the world not having access in electricity. Greece is a Mediterranean country with the unique characteristic of having about 6000 islands, of which only a few hundred are inhabited. Greek islands have great potential for renewable energy sources (RES). However, only a percentage of almost 10% of the total installed renewable capacity is included on non-interconnected islands (NIIs). In addition, non-interconnected islands have small power systems, thus are dependent on Autonomous Power Systems (APS) which are considered both expensive and not environmentally friendly (since they consume diesel or heavy oil (mazut)). The weighted average of the variable cost for all the Greek NIIs electrical systems was rated at 130.519 €/MWh, between 2014 to 2017 [1] and hence it is extremely high. The interconnection of all Greek islands with the mainland grid is an expensive project, but remains a high priority issue for government's energy policy.

The feasible solution to the high costs of electricity production and the reliable supply of electricity in NIIs are hybrid systems. The main objective of this paper is the design of an off-grid, autonomous hybrid system/microgrid for the electrification of Donoussa island, Greece. Based on the load profile of Donoussa island different schemes/scenarios of hybrid renewable energy systems are examined, using HOMER Pro software. Three main scenarios are examined with different percentage rate of renewable energy penetration. The optimal hybrid system configuration of each scenario is selected based on Excess Electricity parameter, Net Present Cost and Levelized Cost of Energy.

2. Literature Review

Because of the broad research and potential for application there is a wide range of published literature and specifically there are studies that examine the optimal design of a hybrid system via HOMER software for Greece. The study in [1], reviews the autonomous electricity systems deployed on Greek islands and examines different scenarios for the purpose of re-structuring the autonomous power system of Astypalea, aiming to reduce energy production costs in a sustainable way. Ref. [2] explore the sustainable planning of a renewables-based energy system aiming to replace the existing diesel generators with a wind-pv-hydrogen hybrid system in Karpathos island, Greece. In addition, authors in [3] explore the potential deployment of aRES-hybrid system for a small Greek island (Agios Efstratios) in three different case scenarios. They aim to establish the optimal design of the microgrid with the less effective cost through a techno-economic analysis. A study on the island of Lesvos, Ref. [4] explores the pumped hydro storage renewable energy system using a computational algorithm and concludes that 25% of the island's energy demand can be met by renewable energy systems in an economical manner. All studies mentioned above used HOMER software for optimization and simulation. Furthermore, a technical and economic study of a hybrid power plant, towards 100% electricity production is discussed in [5], for the autonomous island of Sifnos, Greece, in the context of the initiative of the Sifnos Island Cooperative (SIC) towards energy independence and sustainable development for the local community. In [6] there is a reference to a HRES in Fournoi island, in the eastern Aegean sea, which uses hydropower in order to generate electricity and to cover drinking and agricultural irrigation demands through desalination of sea water. The operation of a pilot hybrid power system using as storage devices sodium sulfur (NaS) batteries, as part of the autonomous power system of Samos Island, is studied in [7]. A flexible power plant is modelled in [8], associated with a Multi-Objective Particle Swarm Optimization to obtain the optimal size of each plant component and the configuration located in Tilos islands, Greece. Finally, [9] analyses and models a generic hybrid power system installed on the island of Crete, Greece.

Besides Greece, there are many other studies that examine the feasibility on hybrid energy systems on islands. In [10] HOMER software is used to determine the most cost effective configurations of a hybrid autonomous energy generation system on St. Martin's island in Bangladesh. Moreover, Refs. [11,12] highlight a hybrid system composed of wind turbines, solar PV, diesel generators, micro-hydro plant and batteries in order to cater for the electricity demand of the Calayan island in the Philippines and Fiji islands respectively. In [13] the technical and economical viability of hybrid energy system in the Masirah Island power system in Oman is examined through HOMER and DIgSILENT software. A study in [14] discusses the techno-economic evaluation of a 100% renewable hybrid system on a remote island. The research in [15] proposes a mathematical model to analyze the effect of varying saturation for a hybrid PV-wind-battery system for Jiuduansha island near Shanghai. Moreover, authors in [16] use linear programming or optimal design of hybrid power generation system where conventional units and renewable energy generators are integrated in order to supply electricity to islands isolated from the national grid. In [17], at Sebira Island system, Kepulauan, a hybrid system implementation planning, following optimal sizing as well as an operational strategy of hybrid PV-Diesel-battery storage system is presented. Authors in [18] propose the design of a hybrid wind-solar-fuel cell power plant along with a power management strategy for TUNeIT [TUNisia and ITaly] Project, in which of four artificial islands are implemented in order to connect Bon (Tunisia) and Pizzolato (Sicily). Besides the off-grid and autonomous applications, grid-connected hybrid systems are examined. In [19] an optimal off-grid and a grid-connected hybrid system is proposed to cover the load demand of Bozcaada island, Turkey.

As mentioned earlier hybrid systems provide electricity not only on islands but in remote areas, communities, houses and buildings (schools, university campus, etc.). Fortunately, remote areas typically possess a wealth of locally available renewable energy resources. In [20–23] microgrids for the support of university buildings, academic institutions, university campuses and of an electric machinery laboratory are examined. The study in [24] employs MATLAB/Simulink and HOMER software to produce a techno-economic analysis and optimum design for a hybrid grid-independent system for the residential and agricultural requirements of an energy poor community in India. Another study proposes Cuckoo Search, a new metaheuristic algorithm, for the solution of the hybrid energy system optimization problem in a remote area located in Almora district of Uttarakhand, India [25]. Refs. [26–30] carry out analyses of off-grid microgrids for the electrification of remote areas in Greece, Cameroon, Nigeria and Malaysia.

Some of the studies mentioned above were employed in remote areas with no access to electricity, others to support buildings and others for islands. The design of each hybrid system is different and is dependent on the available climatic data and load profile in each different case study. There are only a few studies which take into consideration the excess electricity factor for the optimum design and the techno-economic analysis for the hybrid system. Excess electricity is a very important parameter which defines the stability, the reliable supply of the system and the economic viability of a hybrid system. In [31] the authors aim to investigate the existence of excess electricity in an isolated hybrid system in Nepal and discuss the impact of excess electricity on the hybrid system's cost and performance. To address this flaw, this work aims for the optimal design of hybrid system for a non-interconnected island in Greece (Donoussa) with the minimum percentage of Excess Electricity and the most cost-effective NPC and LCoE. In general, there are no specific studies in small or large islands with great fluctuations in their load demand. More specifically, this paper examines the techno-eonomically feasibilty and viability of a hybrid system in Donoussa island with different load demands depending on the season, with high load demands during season months.

3. Methodology, Modelling and Optimization of the Hybrid System

3.1. Methodology

The methodology adopted in the present paper is depicted in Figure 1. The extraction of the optimal configuration is formulated as an optimization problem. This problem includes the objective function, decision variables and limitations. The methodology is composed by the following stages:

Stage 1: Data collection

The sizing of the hybrid system is based on the load characteristics, i.e., peak load and daily load profile. The peak load determines the minimal installed capacity of the hybrid system. For instance, the total power of the PV system should be greater than or equal to the peak load. The seasonality of the load profile determines the evolution of generation profile within the year. The meteorological data determines the availability of the renewable energy resources units. The technical data relate to the operational characteristics of the units. The economic data refer to the economic landscape of the country. For instance, the nominal discount rate is influenced by the state of the country's economy. Finally, the financial data refer to the installation, operation and maintenance costs of the units.

Stage 2: Formulation of the optimization function

It refers to the Net Present Cost (NPC). The scope is to serve the load during all the period of the techno-economic analysis. The limitations of the optimization problem refer to operational constrains of units, for instance restrictions to the operational hours due to scheduled maintenance within the year. The decision variables are the installed power of each units. Thus, the scope of the analysis is to define which combination of the hybrid systems, i.e., the exact configuration of generation units, leads to lower NPC during the technical lifetime of the installation.

Stage 3: Analysis of the results

The results are distinguished to optimization results results. The optimization results provide a hierarchy of all candidate combinations. The combinations are sorted based on the NPC that result to.

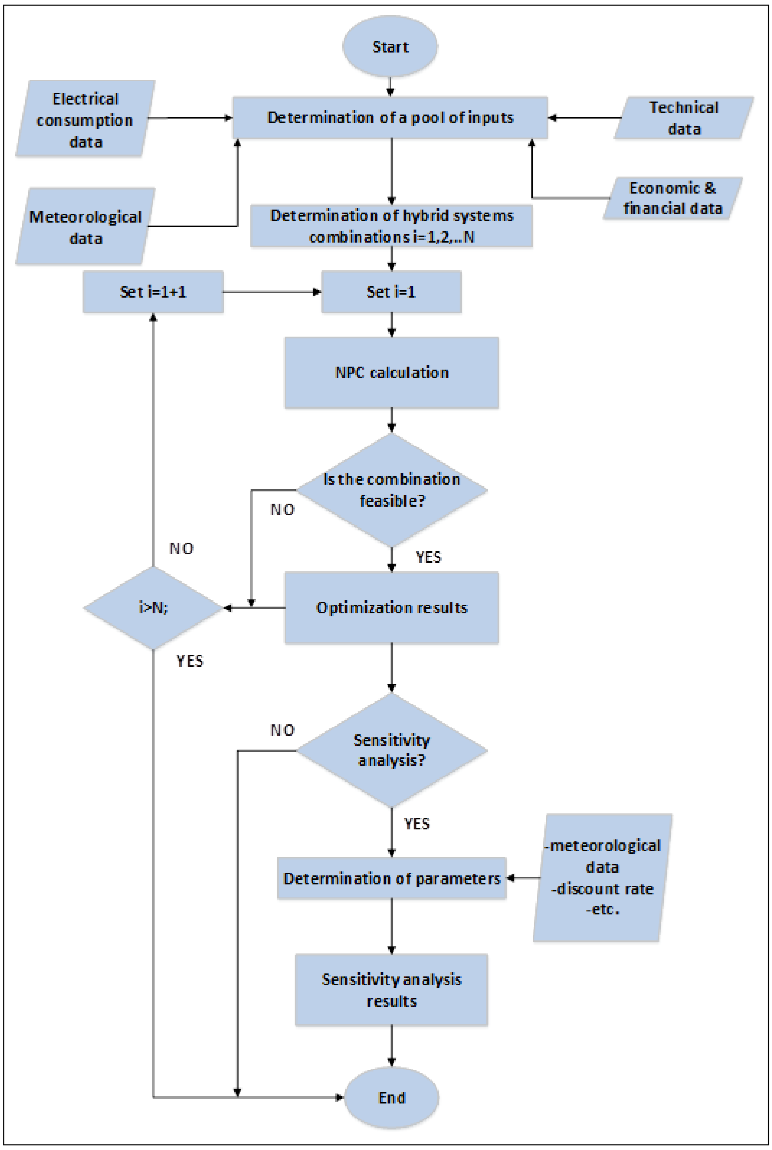

Figure 1. Flow-chart of the methodology.

3.2. Donoussa Island's Electricity Load and Existing Power System

Donoussa island is a small Greek island situated in the Aegean Sea, in the southeastern Cyclades. Donoussa's permanent population is 167, according to the last census. The island is a tourist destination, during the summer months resulting in increased energy demands during this period. In the HOMER modelling tool the first parameter that has to be imported is the electricity load. The load profile for Donoussa island was retrieved from HEDNO (Hellenic Electricity Distribution Network Operator), at an hourly base for the year 2017. Figure 2 shows the annual electric load of Donoussa and the variation of the electricity load during the day. There is a peak in the electrical load of 450 kW in August and the average consumption of the island is 3460.30 kWh/day with an average load of

144.18 kW. In general, the increases of load are observed during the period from July to September, which is the high season of tourism.

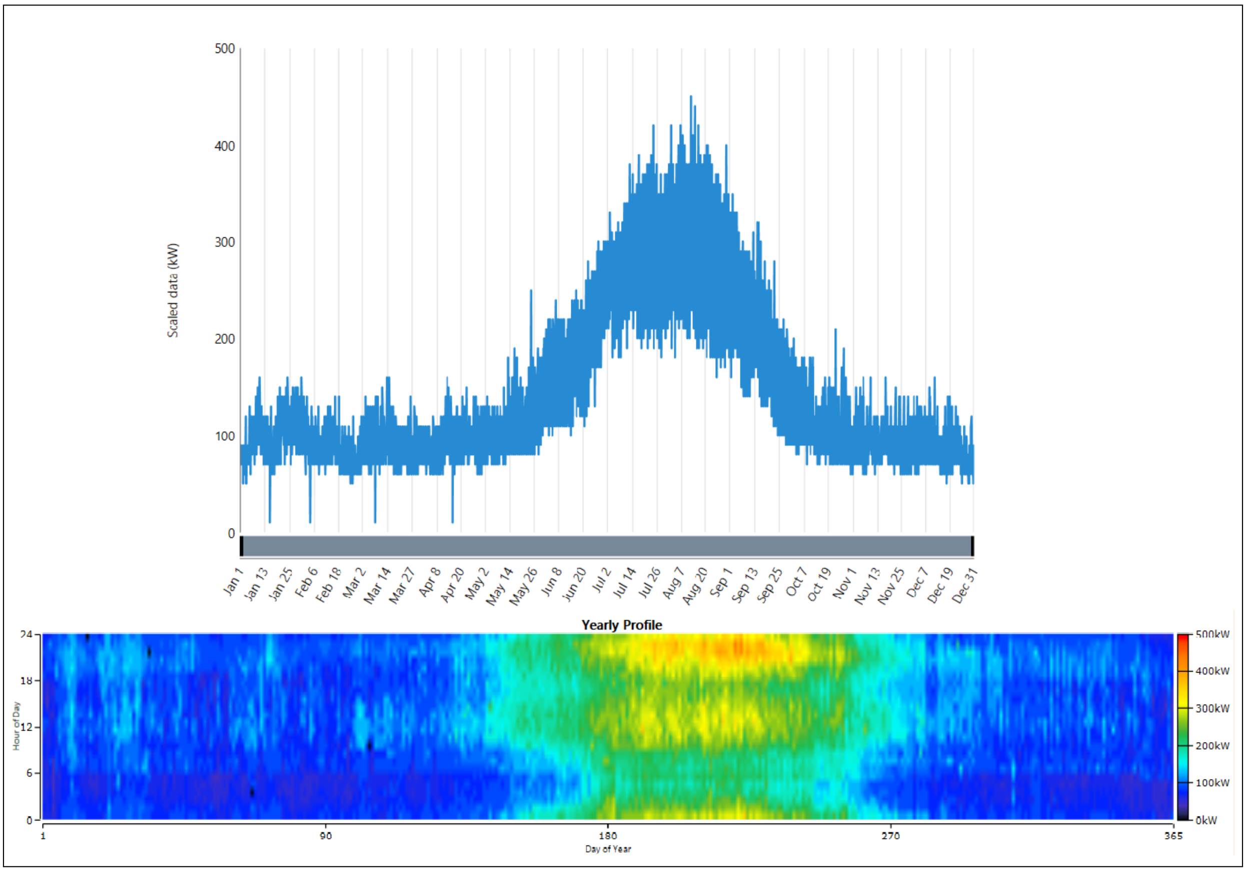

Figure 2. Annual load of Donoussa and Data-Map of the monthly load profile.

Donoussa is one of the 32 greek NIIs. Its energy system is mainly based on one diesel power plant for the production of electricity, without the use of RES so far. The types of generators used in the thermal plant and their characteristics can be seen in the Table 1. The sum of output power of all generators is 0.940 MW and the total production for the year 2017 according to HEDNO was 1012.66 MWh. The average annual variable fuel cost of conventional units is 250.02 €/MWh for 2017 and the average annual additional operating and maintenance cost was estimated to 4.04 €/MWh. The total cost, which includes fuel cost, operating and maintenance cost, amortization of capital, interest payment and auxillary cost for the conventional system power plant was 662.71 €/MWh.

Table 1. Types of generators and their characteristics of Donoussa thermal plant provided by HEDNO [32].

No.	Type of Generator	Fuel	P_{max} (MW)	P_{min} (MW)
1	MAN D2566ME	DIESEL	0.080	0.045
2	MAN D2566ME	DIESEL	0.080	0.045
3	MAN D2566ME	DIESEL	0.080	0.045
4	VOLVO PENTA TAD 1345GE	DIESEL	0.250	0.100
5	VOLVO PENTA TAD 1345GE	DIESEL	0.250	0.100
6	VOLVO PENTA TAD 740GE	DIESEL	0.200	0.110

3.3. Solar Irradiation Data and Wind Resource Assessment

The daily radiation per month was imported in the HOMER software. Global horizontal irradiation data were retrieved from the Photovoltaic Geographical Information System for year 2016 for Donoussa island (latitude is 37.10656, longitude is 25.81385). The annual average solar global horizontal radiation is 5.42 kWh/m^2/day. The solar radiation data can be seen in Table 2. Figure 3 shows the Monthly Solar Radiation Sources and Clearness Index. Similar to solar resources, wind speeds at 50 m above ground level, from NASA Prediction of Worldwide Energy Resource (POWER), were imported into the HOMER software. Table 3 shows the average monthly wind speed of Donoussa. The average annual wind speed is 7.10 m/s. Inputs of monthly average wind speed in HOMER resulted in the comprehensive Figure 4.

Table 2. Donoussa monthly average solar radiation data.

Month	Clearness Index	Daily Radiation kWh/m^2/day
January	0.494	2.339
February	0.617	3.759
March	0.651	5.194
April	0.726	7.133
May	0.658	7.290
June	0.732	8.467
July	0.725	8.194
August	0.717	7.355
September	0.691	5.933
October	0.642	4.258
November	0.585	2.940
December	0.506	2.181

Table 3. Donoussa monthly average wind speed data.

Month	Average Wind Speed (m/s)
January	8.250
February	7.080
March	7.950
April	5.200
May	5.880
June	5.560
July	6.680
August	8.250
September	8.000
October	6.380
November	8.250
December	7.720

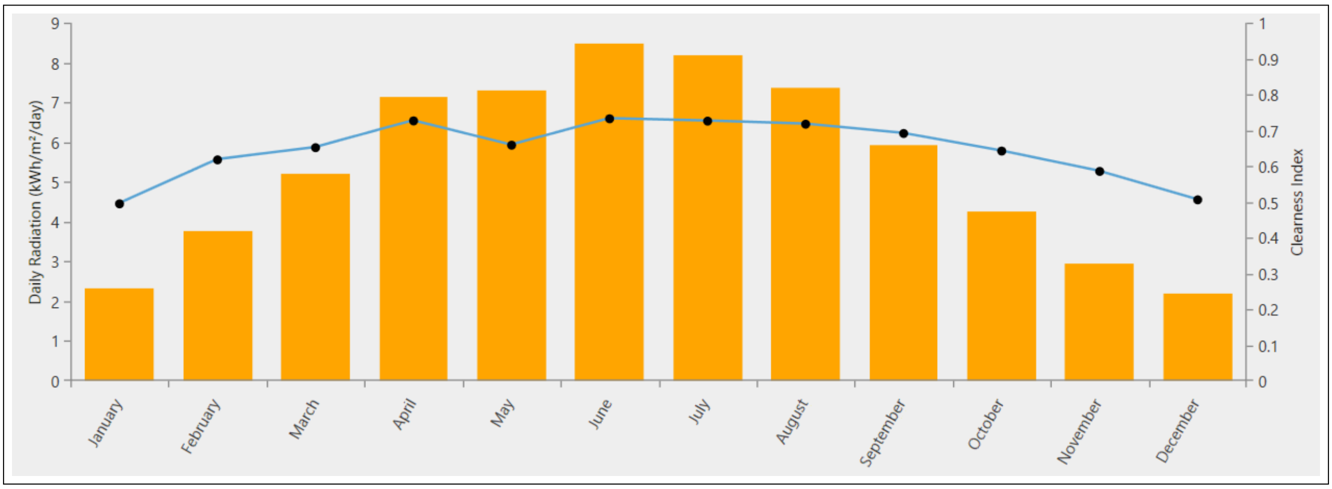

Figure 3. Monthly Solar Radiation Sources and Clearness Index.

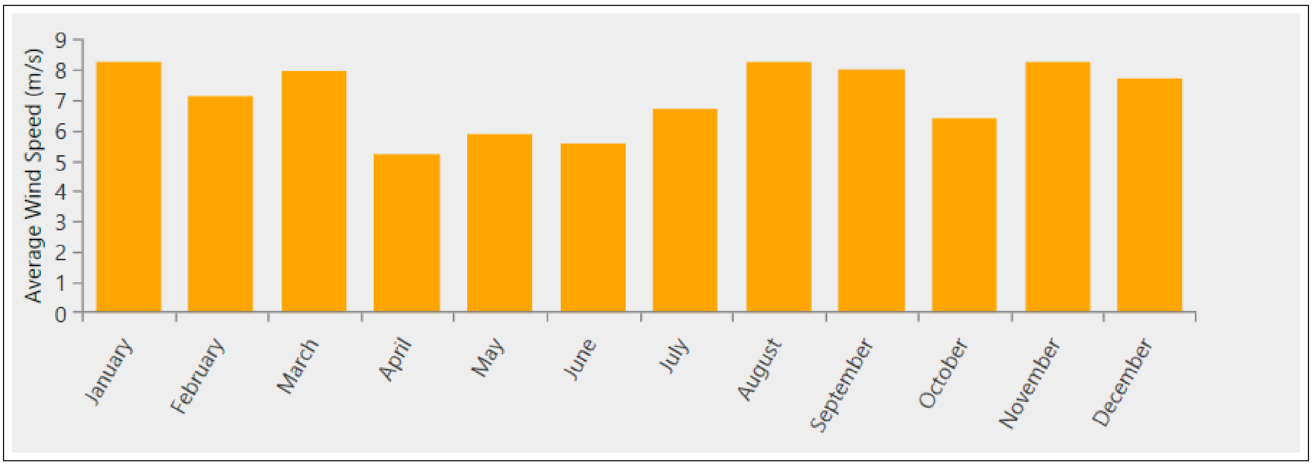

Figure 4. Average monthly wind speed of Donoussa island.

3.4. Simulation Systems—Scenarios

The power system of Donoussa island is composed of 6 diesel generators with total power of about 940 kW which is almost twice as large as the peak load of the system (450 kW). As a result the power system of Donoussa can be considered oversize. To that end, in this study 3 main scenarios were formulated for the electrification of the island of Donoussa.

- The first scenario includes Wind turbines, PV solar panels and five diesel generator units. The renewable fraction of this scenario is considered to be 20%. In the Figure 5 below can be seen the configuration of this scenario.
- As for the second scenario the operation of three diesel generators are dismissed and only three diesel units (200 kW, 250 kW and 80 kW respectively) operate along with wind turbine generators, PV solar panels and battery with a renewable fraction of 50%. Figure 6 depicts the microgrid configuration of the second scenario.
- Finally, in the last scenario it was attempted the feasibility of the system only with RES production without the operation of conventional units. The hybrid system/microgrid consists of Wind turbines, PV solar panels and battery bank. As it is easily understood the renewable fraction of this scenario is 100%. Moreover, two sub-cases are going to be considered. In the first sub-case autonomy days of battery are going to be assumed three and as for the second sub-case five days are assumed. The configuration is depicted in the Figure 7.

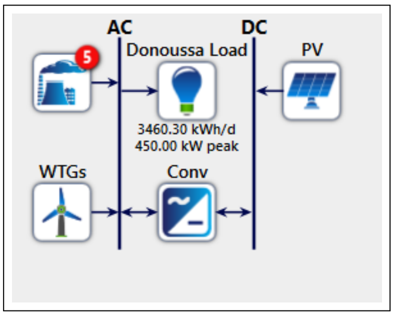

Figure 5. Scenario 1 Homer Pro Configuration.

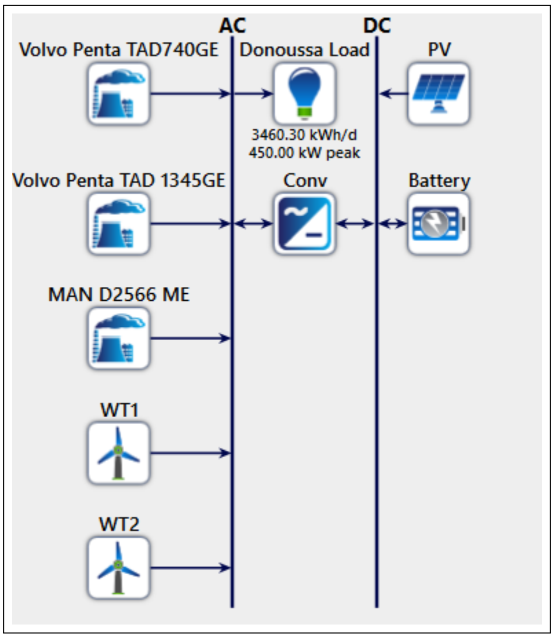

Figure 6. Scenario 2 Homer Pro Configuration.

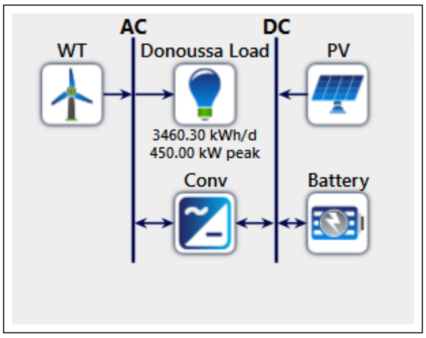

Figure 7. Scenario 3 Homer Pro Configuration.

4. Modelling, Cost Data and Size Specification of Each Component of Hybrid System

4.1. Solar PV Analysis, Size and Cost

PV array is modelled in HOMER software as a device that produces DC electricity using the global solar radiation in direct proportion. The output power of the the PV array is calculated by HOMER bu considering specific values as inputs. Slope, azimuth and ground reflectance are the most important ones and the derating factor of the effect of temperature is applied. Slope is defined as the angle at which the panels are placed relative to the horizontal plane. Typically in fixed-slope PV systems with slope equal to latitude the PV energy production is nearly maximized, in this case 37.10°. The azimuth is the direction that PV panels face. For south this is 0°, for north it is 180°, for east it is −90° and for west it is 90°. PV panels are oriented towards the equator with fixed-azimuth panels and the azimuth is 0° in the northern hemisphere and 180° in the southern hemisphere. Moreover, the fraction of solar radiation reflected on the ground is called ground reflectance. On tilted PV panels, this value is used for the calculation of the radiation incident. This value varies from 3% to 70% depended on the ground cover material and in this study is selected at 20% [19]. When the effect of temperature is taken into consideration HOMER software calculates the power output of PV panels according to the following formula.

$$P_{pv} = W_{pv} \times f_{pv} \times \frac{G_T}{G_S} \times [1 + \kappa_p \times (T_C - T_{STC})] \quad (1)$$

where:
W_{pv} = peak power output in kW,
f_{pv} = derating factor of PV (%),
G_T = solar radiation incident for a specific timeslot in kW/m^2,
G_s = standard test conditions incident radiation number (1 kW/m^2),
κ_p = temperature coefficient (%/C),
T_C = instant PV module temperature (°C),
T_{STC} = standard test conditions PV module temperature (25 °C).

The derating factor is selected at 80% and as a result the production of PV panels is set to 20% in order to model the real-world condition of dust and temperature. After surveying different studies focusing on the cost provided, for this study the Generic flat plate was chosen with a PV panel of 1 kW. The cost of the PV panels varies in different studies and in different countries. The authors considered the capital cost of PV at 620 €/kW, same price also for the replacement cost. These costs include shipping, tariffs, installation, dealer mark-ups and insurances. Operation and maintenance cost are taken at 14 €/year. Lifetime of PV arrays is considered to be 25 years while tracking system is not included in the system of PV panels. The specifications for the chosen PV modules in the current study are highlighted in Table 4.

Table 4. PV technical speciifications and costs.

Parameters (Units)	Value
Panel type	Flat plate
Derating factor (%)	80%
Operating temperature (°C)	47 °C
Temperature coefficient	−0.5
Ground reflection (%)	20%
Lifetime (years)	25 years
Tracking system	No Tracking System
Capital Cost (€)	620 €/kW
Replacement Cost (€)	620 €/kW
Operation and Maintenance Cost (€/year)	14 €/year
Search Space Scenario 1	40, 50, 60, 70, 80, 90, 100 kW
Search Space Scenario 2	180, 190, 200, 210, 220, 230, 240, 250, 260 kW
Search Space Scenario 3 Case 1	1200, 1250, 1300, 1350, 1400, 1450, 1500, 1550 kW
Search Space Scenario 3 Case 2	1400, 1450, 1500, 1550, 1600, 1650, 1700, 1750 kW

4.2. Wind Turbine Modelling, Size and Cost

Wind turbines are machines that extract energy from a steam of air in order to convert it into mechanical energy and then into electricity. The mechanical power captured by a wind turbine can be seen in the formula below [25,29]:

$$P = \frac{1}{2} \times C_p \times \rho \times A \times V^3 \tag{2}$$

where: P = the mechanical power/kinetic power, C_p is the power coefficient, ρ is the air density, A is the area swept by the wind, V the speed of the wind. The choice for the optimal wind turbine for the hybrid system of this study depends on many factors. Depending on the wind speed sources, large wind turbines can be used in the hybrid system or a number of smaller wind turbines. In addition, the relatively low load demand of the island, the quantities of turbines, requiredservice time, hub height, the cost of the component, the type of electricity generated (AC/DC) and cut-in wind speed are some of the constraints on wind turbine choice. The wind turbines selected are the Eocycle EO20 and the Aeolos-H. Rated capacities are 20 kW, 10 kW respectively for Eocycle EO20 and 10 kW for Aeolos-H. According to different studies and market reports initial capital costs differ depending on the study, the capacity of the wind farm (turbine size) and region. The capital cost varies from 1500 €/kW to 2250 €/kW. For this study the capital cost is set at 1800 €/kW and the replacement cost is calculated almost at 80% of the initial capital cost. The operation and maintenance costs are assumed to be 3% of the initial capital cost. Tables 5 and 6 depict parametric inputs of wind turbine for HOMER software, some technical specifications and costs.

Table 5. Technical specifications and Costs of Eocycle EO20 Wind Turbine.

Parameters (Units)	Value
Model	Eocycle EO20
Nominal Capacity (kW)	20 kW
Rotor Diameter (m)	15.8 m
Cut-in/out wind speed (m/s)	2.75 m/s–20.00 m/s
Hub/tower height (m)	36 m
Capital Cost (€)	35,800 €
Replacement Cost (€)	28,640 €
Operation and Maintenance Cost (€/year)	1075 €/year
Scenario 1 Search Space	1, 2 units
Scenario 2 Search Space	1, 2 units

Table 6. Technical specifications and Costs of Aeolos-H 10 kW Wind Turbine.

Parameters (Units)	Value
Model	Aeolos-H 10 kW
Nominal Capacity (kW)	10 kW
Rotor Diameter (m)	8 m
Cut-in/out wind speed (m/s)	3 m/s–10.00 m/s
Hub/tower height (m)	24 m
Capital Cost (€)	17,900 €
Replacement Cost (€)	14,320 €
Operation and Maintenance Cost (€/year)	540 €/year
Scenario 2 Search Space	1, 2 units
Scenario 3 Search Space Case 1	1, 2, 3, 4, 5, 6, 7 units
Scenario 3 Search Space Case 2	1, 2 units

4.3. Batteries Modelling, Size and Cost

In this study after examining different studies for off-grid hybrid systems and micro-grids, lead-acid batteries are chosen due to low cost compared to Li-ion batteries. The model which is input through the HOMER tool library is the Hoppecke 24 OPzS 3000 from the manufacturer Hoppecke which is a lead-acid, deep-cycle type battery. Nominal capacity of this battery is 3570 Ah (7.15 kWh) with a nominal voltage of 2 Volt. After surveying the market of batteries for the specific model, initial capital cost varies from 890 € to 1530 €. Initial capital cost is considered 1200 €, replacement cost for battery is assumed about 70% of its capital cost, that is 840 € and operation and maintenance, is 12 €/year/battery. In Table 7 can be seen the battery characteristics given by the manufacturer and the costs of the battery. In order to determine the optimal number of units for each scenario, a rough approximation is performed based on the methodology described below. According to the following formula the total required capacity of the battery bank (Ah) is calculated [3]:

$$C_{tot,cap} = \frac{n_{day} \times E_L}{\eta_{bat} \times DOD \times V_{bat}} \tag{3}$$

where:
$C_{tot,cap}$ = total required capacity of the battery bank (Ah),
n_{day} = number of autonomy days of the system secured by the storage device,
E_L = average daily energy consumption (kWh),
η_{bat} = overall battery and inverter efficiency,
DOD = Depth of Discharge of the battery (%),
V_{bat} = battery nominal voltage (2 Volt).

E_L is 3460.3 kWh for this study. Overall battery and inverter efficiency is calculated at 0.82, Depth of Discharge of the battery (DOD) is 0.7 and the number of autonomy days of the battery is selected for Scenario 2 n_{day} = 1 and for Scenario 3 (Wind-PV-Battery) n_{day} = 3 and n_{day} = 5. So $C_{tot,cap}$ for Scenario 2 is calculated at 3014.2 Ah and for Scenario 3 at 9042.6 Ah and 15071 Ah respectively. After that the total number of batteries is calculated using the equation.

$$n_{batteries} = \frac{C_{tot,cap}}{C_{single}} \tag{4}$$

where: $n_{batteries}$ is the number of the required batteries, C_{single} is the capacity of a single battery (7.15 kWh) for this study. As a result of the above, the number of batteries for Scenario 2 is estimated at 422 batteries and for Scenario 3 at 1264 or 2108 batteries, depending on the days for autonomy. The DC bus voltage is considered at 24 Volt. The nominal system voltage of the DC bus (48 Volt) should be equal to the overall voltage produced by the total number of strings of the battery. The number of strings are calculated according to the next formula. The voltage of a single bus as mentioned earlier is 2 Volts, so each string is going to contain 12 batteries (12×2 V $= 24$),

$$n_{string} = \frac{n_{batteries}}{V_{DCbus}/V_{bat}} \tag{5}$$

where:
n_{string} = number of strings of the battery,
$n_{batteries}$ = number of the required batteries,
V_{DCbus} = DC bus voltage,
V_{bat} = battery nominal voltage (2 Volts).

According to Formula (5), for Scenario 1 the number of strings is equal to 35.16, approximated to integer 35 strings corresponding to 420 batteries. In addition, as for Scenario 3 with autonomy days, n_{day} = 3, the number of batteries was 1264. Using Equation (5) the number of strings is calculated at 105.33 approximated to 105 strings and the number of batteries decreases at 1260. For the second sub-case with autonomy days, n_{day} = 5 the calculated number of batteries was 2108 and number of strings according to Formula (5) is 175.66, approximated to integer 176 strings corresponding to 2112 batteries.

Table 7. Technical specifications and costs of Hoppecke 24 OPzS 3000 battery.

Parameters (Units)	Value
Nominal Voltage (V)	2 V
Nominal Capacity (kWh)	7.15 kWh
Maximum Capacity (Ah)	3570 Ah
Round efficiency (%)	86%
Minimum State of Charge (%)	30%
Maximum Charge Current (A)	610 A
Lifetime (years)	20 years
Capital Cost (€)	1200 €
Replacement Cost (€)	840 €
Operating and Maintenance Cost (€/year)	12 €/year

4.4. Converter Size and Cost

A converter is an essential part of the hybrid system in order to maintain the balance of energy between AC and DC. A converter can operate as both an inverter and a rectifier. In this study the efficiency of the inverter and the rectifier is set at 90% and 85%, respectively, while the lifetime is set at 15 years. The initial capital cost of converter according to [1], is 250 €/kW and operational and maintenance cost is 230 €/kW. Converter sizes considered in this study are: Scenario 1: 80, 90, 100 and 200 kW, Scenario 2: 100, 200, 300, 400 and 500 kW and Scenario 3: Case 1 400, 410, 420, 430, 440, 450, 460, 470, 480, 490 and 500 kW and Case 2 200, 250, 300, 350, 400, 450, 500, 550 and 600 kW.

4.5. Economic Inputs

4.5.1. Net Present Cost (NPC)

HOMER software calculates the NPC of each proposed power system and ranks them in descending order based on NPC. The NPC of a system is the present value of all costs during its life minus revenues and present value of the system. It is an important indicator as it shows if the whole investment is profitable or not. The NPC is given by the formula below [9]:

$$NPC = \frac{C_{ann,tot}}{CRF(i, R_{proj})} \tag{6}$$

where:
$C_{ann,tot}$ = total annualized cost ($/year),
CRF = capital recovery factor (calculated in Formula (7)),
i = real discount rate,
R_{proj} = project lifetime.

The real discount rate was considered at 4.25% and the inflation rate at 0% according to the Bank of Greece [33], so the expected real discount rate calculated from Formula (7) is 4.25% and it is used for the calculation of the NPC cost. In addition, project lifetime is set at 25 years and all the costs are measured in the currency of Euro. The capital recovery factor (CRF) is a formula which is used for the calculation of the present value of an annuity. The equation of CRF can be seen below.

$$CRF(i, N) = \frac{i \times (1+i)^N}{(1+i)^N - 1} \tag{7}$$

where N is the number of years, i is the real discount rate.

4.5.2. Levelized Cost of Energy (LCoE)

Levelized cost of Energy (LCoE or COE) is defined by HOMER as the average (cost/kWh) of useful electrical energy produced by the system. This quantity is calculated from the following equation.

$$COE = \frac{C_{ann,tot} - c_{boiler} \times H_{served}}{E_{served}} \tag{8}$$

where:
$C_{ann,tot}$ = total annualized cost ($/year),
c_{boiler} = boiler marginal cost ($/kWh),
H_{served} = total thermal load served (kWh/year),
E_{served} = total electrical load served (kWh/year).

E_{served} is calculated by adding AC primary load served (kWh/year) ($E_{pr,AC}$), DC primary load served (kWh/year) ($E_{pr,DC}$) and total grid sales (kWh/year) ($E_{gr,sales}$). In this study, no energy sale to the grid is considered [34].

4.6. Excess Electricity Assessment

Excess Electricity is surplus energy that is produced in a hybrid system. This energy cannot be directed to neither load demand nor the batteries and therefore it must be dumped or curtailed. It is usually produced by the intermittent nature of RES when battery is not able to store the Excess Electricity because it is fully charged or by a generator when its minimum output exceeds the load. Excess Electricity is an important parameter for the voltage and frequency stability of the system and must be zero in order for the system to operate in a stable manner and supply electricity reliably to consumers. Excess power can be usable in many ways. Desalination systems like Reverse Osmosis especially on islands can use the excess power for their operation. Besides, Excess Electricity can be reused for the cooling and the heating of households. The surplus energy that the system is not able to use, might be dispersed in a dump load, typically a simple resistive heater or a bank of light bulbs.

5. Results and Discussion

In this chapter we discussed the optimization results for each scenario. The assessment covers both the technical and economical system performance for 20 years lifetime. Optimization results are studied in respect with the lowest Excess Electricity Energy which is a factor that can cause a lot of stability problems and is the main parameter guiding the selection of the optimal system for each scenario. Then the optimal hybrid system is selected with respect to the lowest NPC and LCoE.

5.1. Optimization Results for Scenario 1/Diesel-PV-Wind Hybrid system

The optimization results can be seen in the Table 8 for Scenario 1. The most optimal Hybrid Renewable Energy System to meet the load demand of Donoussa island for this scenario, consists of: 100 kW PV, 2 Eocycle Wind Turbines, 5 operating conventional units (diesel generators) and 1 converter of 80 kW. The Excess Electricity percentage is very low at 6.68% (90,807 kWh/year) and the RES participate in the production as a percentage 20.2% over the RF limit. The dispatch strategy that is used is Cycle Charging, with NPC at 4,950,408 € and LCoE at 0.2948 €. The total power production of this power system setup is 1,359,120 kWh/year. Excess electricity, present in the scenario we studied, does not necessarily indicate inadequacies in system design. On the contrary, sometimes including components that produce more electricity than is required is more economical for the system, rather than to invest on excess electricity storage infrastructure. Moreover, excess electricity can be reused for heating and cooling load for households as well as in desalination systems. The detailed production of each component and their technical characteristics can be seen in Table 9. Some useful remarks regarding Scenario 1 can be derived from Table 9. The load demand on the island is satisfied with 5 out of 6 diesel generators of the existing power systems. The main production to cover the needs of the island in this scenario comes from diesel generators which are already installed on the island. Conventional units produce nearly 74.18% of the total production. The low operational hours of Diesel generators (TAD 1345GE 855 h/year) suggest that the system could cope with fewer conventional units (Scenario 2). In this specific scenario RES produce 20.2% of the total production of electricity for the island load demand. The monthly electrical production of each component can be seen in Figure 8. The diesel generator Volvo Penta TAD1345GE seems to operate many hours during the summer months when load demand is high due to tourism. The total fuel consumed is 249,215 diesel L/year with heavy fuel emissions.

Table 8. Scenario 1 Optimization results.

Systems	PV (kW)	EO20 (WT)	TAD 740GE (kW)	TAD 1345GE (kW)	TAD 1345GE (kW)	D2566 ME (kW)	D2566 ME (kW)	Conv (kW)	Excess Elec (%)	NPC (Millions €)	COE (€)	Ren Frac (%)	Dispatch
System 1	100	2	200	250	250	80	80	80	6.68	4.95	0.295	20.2	CC

Figure 9 and Table 10 depict the output power and the electricity simulation results of solar PV. Electricity generation is maximized in January, February and November. The rated capacity of PV panels on this scenario is 100 kW with a maximum power output of 88.6 kW. The total hours of operation of solar PV panels is 4386 h/year and it can be easily deduced that PV panels work almost 12 hours per day. As far as Wind Turbines are concerned, power output by the Wind Turbines is depicted in Figure 10. It is high throughout the year with a maximum of 40.6 kW in February. Furthermore, wind penetration is at a low percentage 14.7% due to the 2 wind turbines are used in this scenario. Table 11 shows the Wind Turbines scheme simulation results.

Table 9. Analytical Electrical Production and technical characteristics for optimal configuration of Scenario 1.

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption L/year	Operational Hours h/year
PV	164,853	12.1	18.8	-	4386
TAD740GE	151,860	11.2	112	36,447	1353
TAD 1345GE	509,656	37.5	150	119,781	3396
TAD 1345GE	9486	0.698	112	2,229	85
MAN D2566 ME	234,188	17.2	45	27,737	2291
MAN D2566 ME	103,095	7.59	47.1	63,022	4976
Eocycle EO20	185,982	13.7	21.2	-	7708
Total	1,359,120	100	-	249,215	-

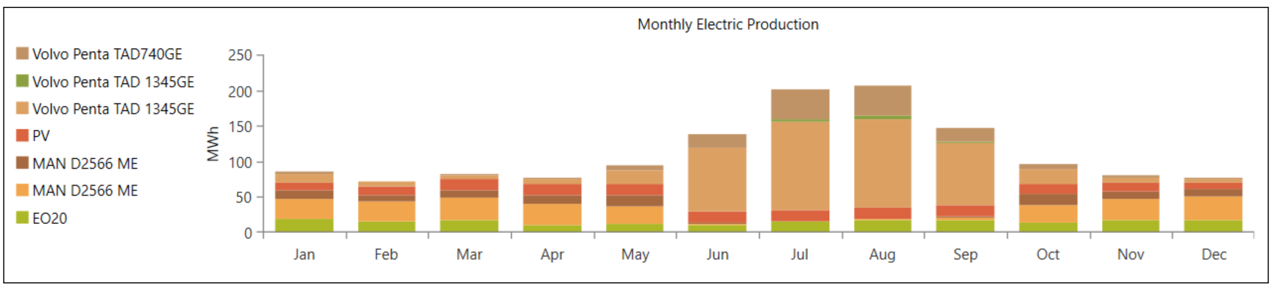

Figure 8. Monthly Electrical Production of Scenario 1.

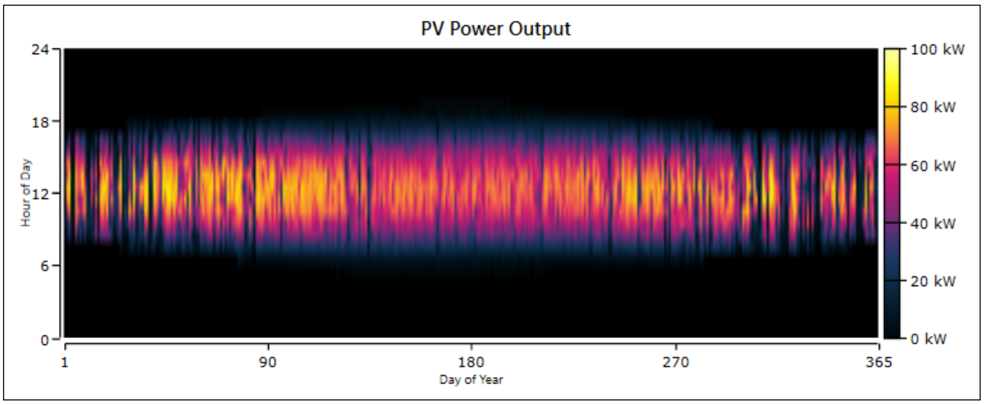

Figure 9. PV Power output.

Table 10. PV Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	100	kW
Minimum Output	0	kW
Maximum Output	88.6	kW
Mean Output	18.8	kW
Mean Output	452	kWh/d
Capacity Factor	18.8	%
Total Production	164,853	kWh/year
PV Penetration	13.1	%
Hours of Operation	4386	h/year
Levelized Cost	0.0343	€/kWh

Table 11. Wind Turbines Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	20	kW
Minimum Output	0	kW
Maximum Output	40.6	kW
Mean Output	21.2	kW
Capacity Factor	53.1	%
Total Production	185,982	kWh/year
Wind Penetration	14.7	%
Hours of Operation	7708	hrs/year
Levelized Cost	0.0405	€/kWh

Regarding the system costs, the optimal configuration was selected according to the minimum NPC cost and LCoE. The main economic aspects for the optimal system are presented in Table 12. It can be easily seen that the main cost of the selected configuration is the fuel costs with a value of 4,595,337.32 €. This can be justified from the fact that diesel generators operate in order to satisfy the load demand and the fuel consumption happens at very high rate. The Initial cost/Capital cost is very low since diesel generator units have been already installed in power system of Donoussa. Cash flow during the lifetime of the project is depicted in Figure 11. In addition, the main source of costs comes from diesel generators and more specifically from VOLVO PENTA TAD1345GE with total cost of 2,305,670.09 € and then the rest diesel generators follow. On the other hand, the RES (Wind Turbines and PV panels) have a little share of the total NPC of the hybrid system. Detailed costs by each component are depicted in the Table 13.

According to HEDNO the power station of Donoussa island produced 1012.66 MWh in 2017. In addition, the average annual variable cost of conventional units of the Donoussa power system for the year 2017 is equal to 250.02 €/MWh. The total annual cost can be easily calculated at 253,185.25 € and if it is considered an average yearly cost, for lifetime of 20 years the total cost of the existing power system of Donoussa is 5,063,705.06 €. The total NPC of Scenario 1 is 4,950,407.61 € which is a lower value from the cost for the existing power system by 113,297.45 €. This observation makes the optimal configuration of Scenario 1 feasible and economical viable for Donoussa island.

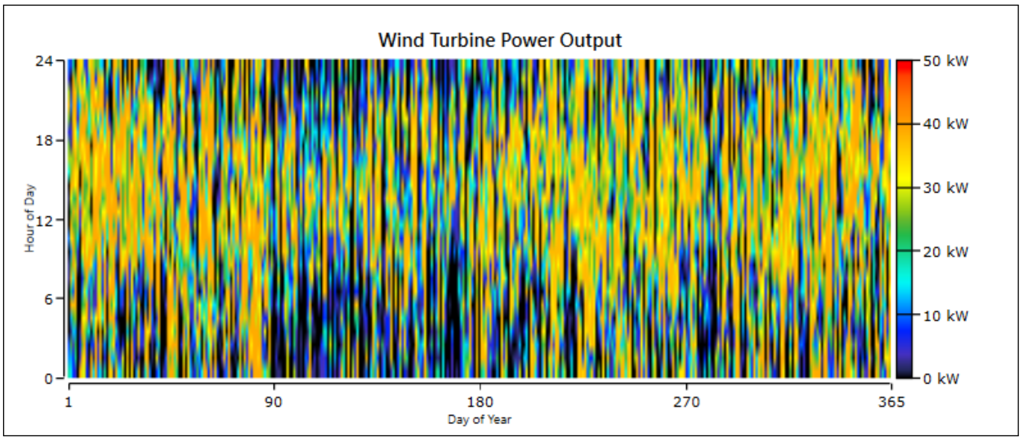

Figure 10. Wind Turbine Power output.

Table 12. Economic characteristics of the optimal configuration of Scenario 1.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/year)	Fuel (€)
Optimal	4,950,407.61	0.2948	153,600	175,581.04	−36,535.63	62,424.89	4,595,337.32

Table 13. Analytical costs of each component Scenario 1.

Component	Capital (€)	Replacement (€)	O & M (€)	Fuel (€)	Salvage (€)	Total (€)
Eocycle E020	71,600	0.00	28,556.30	0.00	0.00	100,156.30
Generic Flat plate PV	62,000	0.00	18,612.11	0.00	−5393.87	75,218.24
Generic large, free converter	20,000	9855.46	0.00	0.00	−5335.87	24,519.59
MAN D2566 ME	0.00	36,378.24	3969.17	1,162,073.04	−125.28	1,202,295.17
MAN D2566 ME	0.00	15,555.28	1827.44	511,442.71	−1090.95	527,734.48
VOLVO PENTA TAD1345GE	0.00	98,032.64	6772.15	2,208,667.27	−7801.97	2,305,670.09
VOLVO PENTA TAD1345GE	0.00	0.00	169.50	41,106.68	−14,656.24	26,619.94
VOLVO PENTA TAD1740GE	0.00	15,759.42	2518.22	672,047.62	−2131.45	688,193.81
System	153,600	175,581.04	62,424.89	4,595,337.32	−36,535.63	4,950,407.61

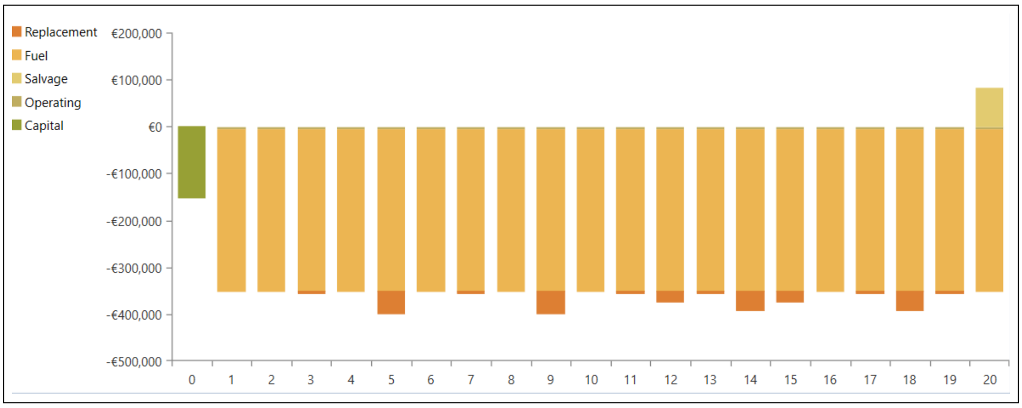

Figure 11. Cash flow by Cost type Scenario 1.

5.2. Optimization Results for Scenario 2/Diesel-PV-Wind-Battery Hybrid System

In Scenario 2 the hybrid system is composed of Wind Turbines, PV panels, battery storage and diesel generators. Renewable fraction for this case is at 50%, after the optimization, the configuration shown in Table 14 is the optimal system. The main target of this Scenario is the reduction of Excess Electricity as well as the NPC, the LCoE and the number of conventional units. Optimal feasible system has Excess Electricity at a 0% rate. The optimal hybrid system consists of 260 kW of Panels, 2 Wind Turbines of type Eocycle EO20 (20 kW), 2 Aeolos-H (10 kW) Wind Turbines, 1 unit of VOLVO PENTA TAD740GE diesel generator, 1 unit of VOLVO PENTA TAD1345GE diesel generator, 1 unit of MAN D2566ME diesel generator, 420 battery units and a converter of 200 kW. Where the diesel generators provided just enough power to serve the load without charging the batteries a load following (LF) dispatch strategy is selected. The NPC is at 4,031,102 € and LCoE at 0.2401 €. Table 15 presents the technical and electrical characteristics of the optimal system. The total power production of this power system setup is 1,307,797 kWh/year. The excess electricity in the current scenario, which can be used in auxiliary services, is also a result of the system design in order to minimize the cost of the components used in the proposed infrastructure. Regarding Table 15 some important remarks can be drawn concerning the optimal configuration of Scenario 2. Comparing to Scenario 1 and with the existing power system of Donoussa island, the hybrid system includes only 3 diesel generator units instead of 5 in system of Scenario 1. The production is divided almost equally between the conventional units and the RES with almost 47.28% of the total production coming from diesel generators and almost 52.7% from RES. The low operational hours of the diesel generator VOLVO PENTA TAD1345GE indicates that with a possible increase in RES the hybrid system could meet the load demand with fewer operational conventional units. The monthly electrical production of each component is presented in Figure 12.

Table 14. Scenario 2 Optimization results.

Systems	PV (kW)	EO20 (WT)	Aeolos-H	TAD 740GE (kW)	TAD 1345GE (kW)	D2566 ME (kW)	Battery	Conv (kW)	Excess Elec (%)	NPC (Millions €)	COE (€)	Ren Frac (%)	Dispatch
System 1	260	2	2	200	250	80	420	200	0	4.03	0.240	51.0	LF

Table 15. Analytical electrical Production and technical characteristics for optimal configuration of Scenario 2.

System Components	Production (kWh/year)	Production %	Mean Output (kW)	Annual Fuel Consumption (L/year)	Operational Hours (h/year)
PV	428,618	32.8	48.9	-	4386
TAD740GE	429,150	32.8	136	109,093	3153
TAD 1345GE	60,600	4.63	111	17,332	548
MAN D2566 ME	128,867	9.85	47.7	34,682	2703
Eocycle EO20	185,982	14.2	21.2	-	7708
Aeolos-H (10 kW)	74,579	5.70	8.51	-	7374
Total	1,307,797	100	-	161,106	-

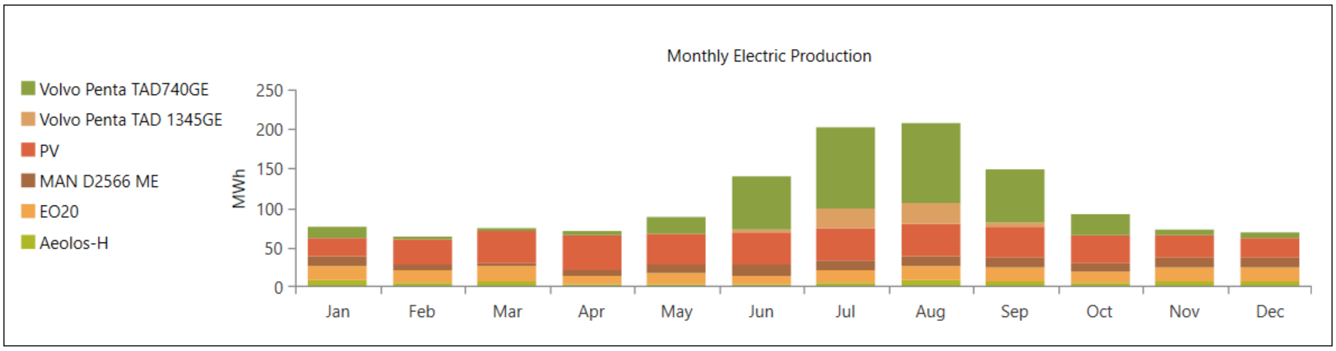

Figure 12. Monthly electrical production of each component of Scenario 2.

The greatest share in electrical production has the generator VOLVO PENTA TAD740GE with 429,150 kWH/year and 32.8% in total production. The maximum power output of VOLVO PENTA TAD740GE occurs during the summer months, that is June-August, due to tourism. On the other hand, the power output is significantly reduced for the rest of the year. As for the other two conventional units of the optimal configuration, as mentioned earlier VOLVO PENTA TAD1345GE operate few hours during the year with a mean electrical output of 111 kW. MAN D2566ME with mean output at 47.7 kW operates 2703 h/year with a stable rate. In addition, the total fuel consumed is 161,106 diesel L/year which is considered a much lower value than fuel consumption in Scenario 1 (249,215 L/year) due to the reduction of conventional units.

Solar PV panels have a great share in the total electrical production of this Scenario with 32.8%. PV have a rated capacity in the optimal system configuration of 260 kW and a mean output of 48.9 kW. There is a clear increase on the rated capacity of PV panels compared to Scenario 1 due to the increase in the Renewable Fraction from 20% to 50%. In Figure 13 and in Table 16 can be observed PV scheme simulation results. As far as Wind Turbines are concerned, the optimal configuration hybrid system includes 4 Wind Turbines, a combination of 2 Eocycle EO20 (20 kW) and 2 of Aeolos-H (10 kW) with a total sum of 60 kW. In this scenario wind energy contributes in electrical production with almost 20% in total electrical production. Wind turbines operate under their mean output only a few months during the year. Wind Turbine scheme simulation results and power output are depicted in Figure 14 and in Tables 17 and 18. Figure 14 highlights the high reliance on wind energy. In this scenario there is an extra important parameter for the hybrid system which is the energy storage. Batteries were solely charged by the RES based on the Load Following dispatch strategy. From Figure 15 one can derive that battery is at low levels of charge during spring and summer months due to the fact that battery has to contribute to energy production to meet the load demand. Battery is at high levels of charge mainly during the winter months due to the high operation of RES. Battery scheme simulation results are presented in Table 19.

The NPC for the optimal system configuration is at 4,031,102.03 € and LCoE is 0.2401 €. There is a sufficient difference between NPC of Scenario 1 and Scenario 2. Table 20 summarizes the financial aspects of the optimal configuration of Scenario 2. It can be easily derived that the main type of costs are fuel costs with 2,970,686.19 €. Fuel costs are almost at half price of fuel costs of Scenario 1. Capital costs are 822,600.00 € and have the second greatest share in total costs of the hybrid system. Capital costs are justified from the purchase, transportation and installation of RES, which have larger rated capacity than in Scenario 1. Cash flow during the lifetime of the project is presented in Figure 16. The analytical costs for each component for the optimal configuration are highlighted in Table 21. High share in the total cost have firstly the two of three conventional units and then battery. The existence of battery in the selected hybrid system increases the cost, in contrast PV panels and Wind Turbines have not such great share in the total cost of the system. Furthermore, replacement costs of Scenario 2 are 112,901.73 € less than Scenario 1 (175,581.04 €) where 4 out of 5 conventional units are included in the replacement costs. The total NPC cost of the optimal configuration of the current Scenario is more economically viable than cost of Scenario 1 and calculated cost of existing power system. Scenario 2 is considered the most economical feasible with a 0% of Excess Electricity. For the period of twenty years, almost one million Euros is saved by this hybrid system configuration while the load is fully satisfied.

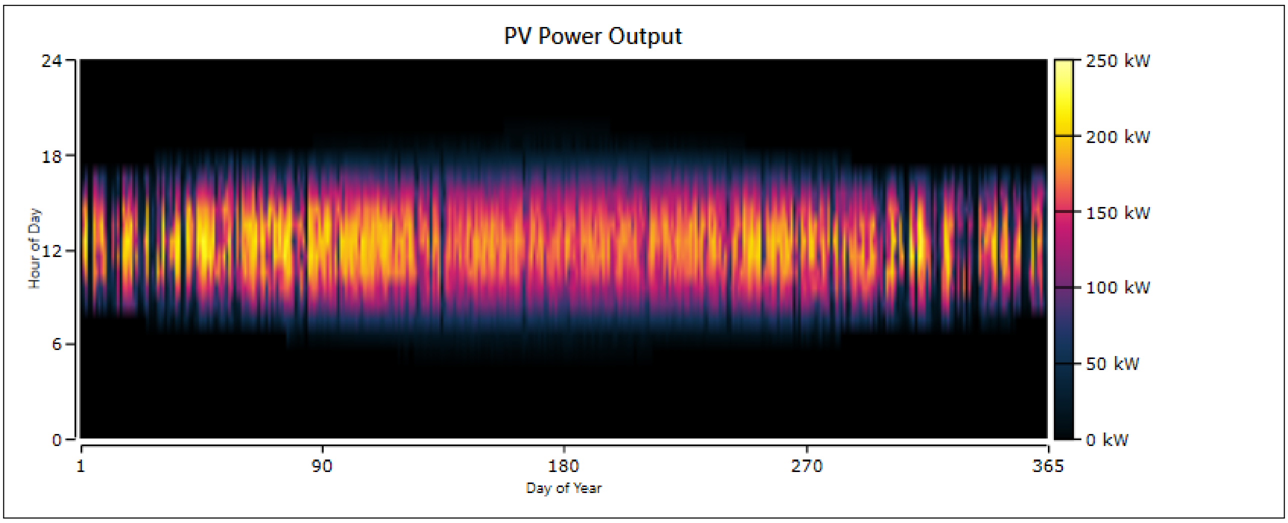

Figure 13. PV power output Scenario 2.

Table 16. PV Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	260	kW
Minimum Output	0	kW
Maximum Output	230	kW
Mean Output	48.9	kW
Mean Output	1174	kWh/d
Capacity Factor	18.8	%
Total Production	428,618	kWh/year
PV Penetration	33.9	%
Hours of Operation	4386	h/year
Levelized Cost	0.0343	€/kWh

Table 17. Eocycle EO20 (20 kW) Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	40	kW
Minimum Output	0	kW
Maximum Output	40.6	kW
Mean Output	21.2	kW
Capacity Factor	53.1	%
Total Production	185,982	kWh/year
Wind Penetration	14.7	%
Hours of Operation	7708	h/year
Levelized Cost	0.0405	€/kWh

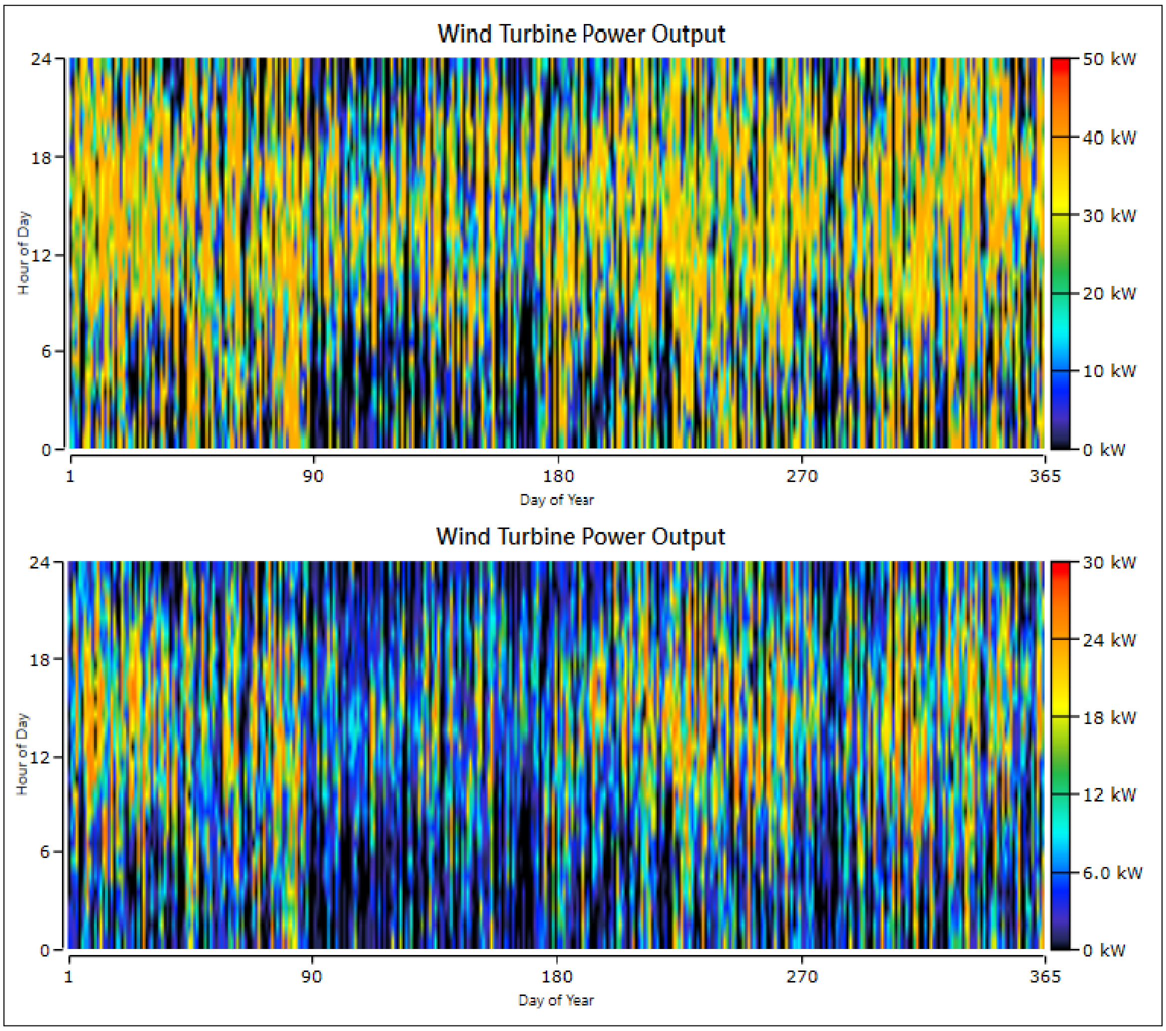

Figure 14. Eocycle EO20 (20 kW) (**upper** figure) and Aeolos-H (10 kW) (**down** figure) power output Scenario 2.

Table 18. Aeolos-H (10 kW) Scheme Simulation Results.

Quantity	Value	Units
Rated capacity	20	kW
Minimum Output	0	kW
Maximum Output	27.6	kW
Mean Output	8.51	kW
Capacity Factor	42.6	%
Total Production	74,579	kWh/year
Wind Penetration	5.9	%
Hours of Operation	7374	h/year
Levelized Cost	0.0506	€/kWh

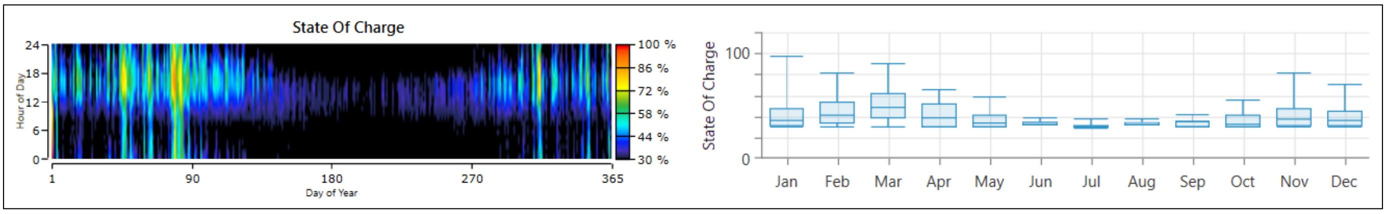

Figure 15. Battery State-of-Charge Scenario 2.

Table 19. Battery Scheme Simulation Results.

Quantity	Value	Units
Batteries	420	qty
String Size	12.0	batteries
Strings in Parallel	35.0	strings
Bus Voltage	24.0	V
Autonomy	14.6	hr
Storage Wear Cost	0.0895	€/kWh
Nominal Capacity	3003	kWh
Usable Nominal Capacity	2102	kWh
Energy In	162,376	kWh/year
Energy Out	141,538	kWh/year
Storage Depletion	2043	kWh/year
Losses	22,881	kWh/year
Annual Throughput	152,625	kWh/year

Table 20. Economic characteristics of the optimal configuration of Scenario 2.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/year)	Fuel (€)
Optimal	4,031,102	0.2401	822,600	112,901.73	−42,539.07	167,453.17	2,970,686.19

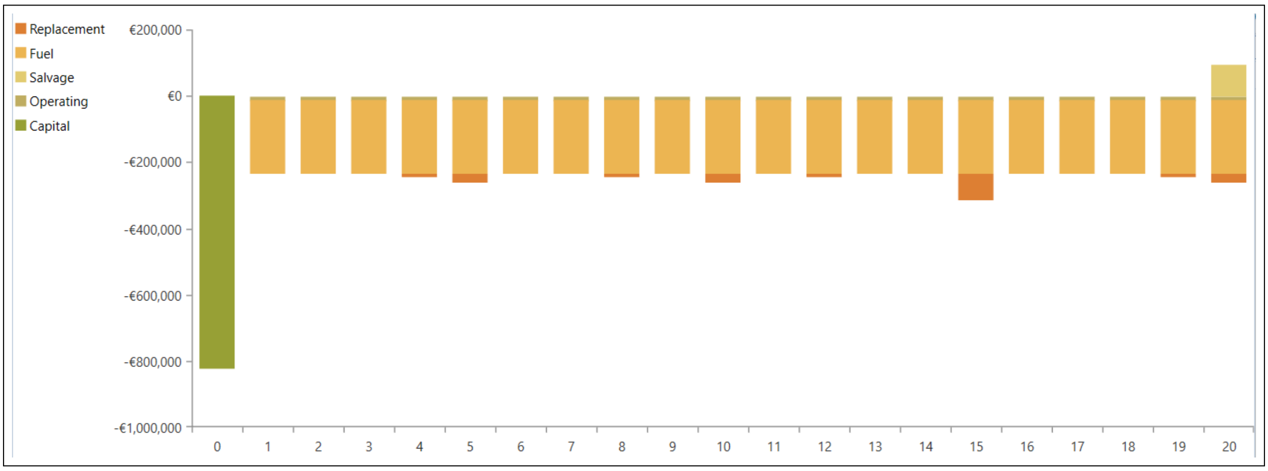

Figure 16. Cash flow by Cost Type Scenario 2.

Table 21. Analytical costs of each component Scenario 2.

Component	Capital (€)	Replacement (€)	O & M (€)	Fuel (€)	Salvage (€)	Total (€)
Aeolos-H 10 kW	35,800.00	0.00	14,357.92	0.00	0.00	50,157.92
Eocycle EO20	71,600.00	0.00	25,582.89	0.00	0.00	100,182.89
Generic Flat plate PV	161,200.00	0.00	48,391.49	0.00	−14,024.06	195,567.43
Generic large, free converter	50,000.00	24,638.65	0.00	0.00	−13,339.68	61,298.97
Hoppecke 24OPzS 3000	504,000.00	0.00	67,003.60	0.00	0.00	571,003.60
MAN D2566 ME	0.00	25,803.75	2156.08	639,502.17	−2067.07	665,394.93
VOLVO PENTA TAD1345GE	0.00	98,032.64	6772.15	2,208,667.27	−7801.97	2,305,670.09
VOLVO PENTA TAD1345GE	0.00	0.00	1,092.80	319,589.11	−4451.97	316,229.93
VOLVO PENTA TAD740GE	0.00	62,459.33	5868.40	2,011,594.91	−8656.29	2,071,266.35
System	822,600.00	112,901.73	167,453.17	2,970,686.19	−42,539.07	4,031,102.03

5.3. Optimization Results for Scenario 3/Wind-PV-Battery

Scenario 3 is composed of a 100% RES. As was observed by Scenarios 1 and 2, is possible for the system to meet the island's load demand with the least number of conventional units. In this scenario all diesel generators were removed from the simulations in order for 100% renewable hybrid system to be examined. An 100% renewable, off-grid system could face electricity supply problems and the uncertainty of the time and the amount of the power delivered to customers. In the current scenario, two cases are going to be examined: one case with 1260 batteries and one with 2112 batteries. For the first case the optimal system includes 1450 kW of PV panels, 7 Wind Turbines (Aeolos-H 10 kW), 1260 Battery units, a 470 kW converter and a Cycle Charging dispatch strategy (CC). The optimal system for the second case of Scenario 3, consists of 1450 kW of PV panels, 2 Wind Turbines (Aeolos-H 10 kW), 2112 battery units, a 450 kW converter with a Load Following (LF) dispatch strategy. The NPC is at 3,759,814.85 € and the LCoE at 0.2241 € for case 1 and for case 2 NPC is 5,217,030.15 € and LCoE is 0.3107 €. However, the two systems face the problem of the unmet electrical load and the capacity shortage at a very small percentage 0.0818% and 0.0997% of Unmet Electric Load and Capacity Shortage for case 1 and 0.00810% and 0.0224% for case 2. In both cases, percentage-wise, those numbers are low, almost zero and are considered easily manageable. As for Excess Electricity percentage, touches almost half of the energy output with 46.8% for case 1 while is at 41.8% for case 2. The total power production of this power system setup is 1,359,120 kWh/year. Like in the previous scenarios, in this scenario the excess electricity is scheduled by system design as a result of reducing the total investment cost of the infrostructure over the spanned period.

Tables 22 and 23 present the technical and electrical characteristics of the optimal system for case 1 and case 2 of Scenario 3.

Table 22. Analytical Electrical Production and technical characteristics for optimal configuration of Scenario 3 case 1.

System Components	Size	Electricity Production		Mean Output (kW)	Operational Hours (h/year)
		kWh/year	%		
PV	1450 kW	2,390,365	90.2	273	4386
Aeolos-H (10 kW)	7 (70 kW)	261,025	9.84	29.8	7374
Total	1520	2,651,391	100	-	-
Battery Hoppecke	1260 (9009 kWh)	Energy in 678,208 kWh/year	Energy out 583,614 kWh/year	Annual throughput 629,327 kWh/year	Autonomy 43.7 h

Table 23. Analytical Electrical Production and technical characteristics for optimal configuration of Scenario 3 case 2.

System Components	Size	Electricity Production		Mean Output (kW)	Operational Hours (h/year)
		kWh/year	%		
PV	1450 kW	2,390,365	97	273	4386
Aeolos-H (10 kW)	2 (20 kW)	74,579	3.03	8.51	7374
Total	1,470	2,464,944	100	-	-
Battery Hoppecke	2112 (15,099 kWh)	Energy in 783,923 kWh/year	Energy out 674,837 kWh/year	Annual throughput 727,696 kWh/year	Autonomy 73.3 h

From Tables 22 and 23 some useful remarks can be derived. In two optimal configurations for the two cases of Scenario 3 it is easily noticed that PV panels have a greater share of energy production. In both cases rated capacity of PV panels is the same. PV panels in both cases are the main source of the supply of electricity in a stable way to Donoussa island because their production is more predictable. Monthly electrical production of each component is depicted in Figure 17 for both cases. PV power output and PV scheme simulation results are highlighted in Figure 18 and Table 24 for both cases. Wind Turbines have a more "auxiliary" role in the Scenario 3 in both cases among with the battery units. This fact can be confirmed from the contribution of them in the electrical production with 9.84% for Case 1 and 3.03% for Case 2. January, March and July are the months that the maximum power output of Wind Turbine appears. Aeolos-H power output for Case 1 and Case 2 is presented in Figure 19. Tables 25 and 26 depict the Wind Turbine Scheme simulation results for the two cases of Scenario 3.

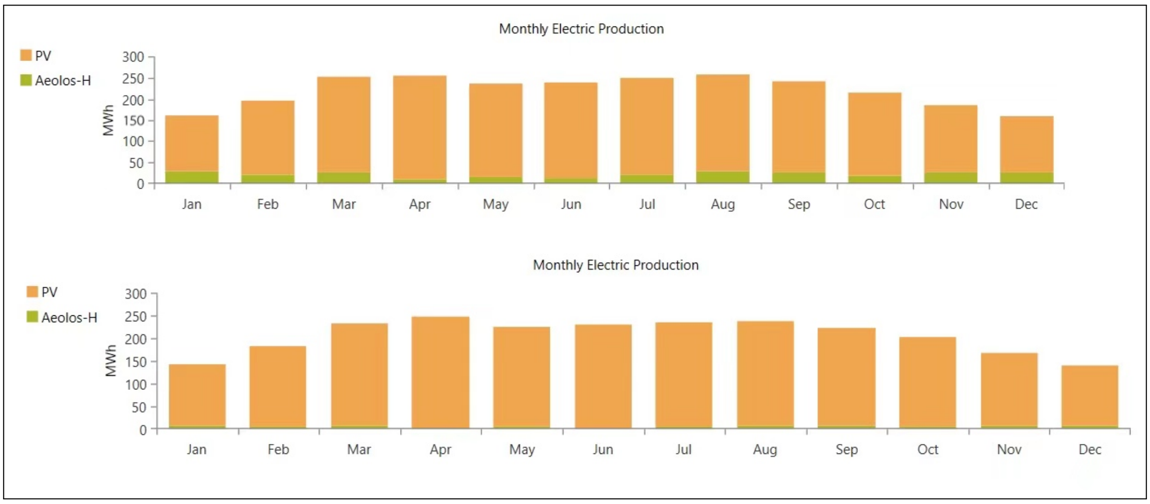

Figure 17. Monthly electrical Production Case 1 (**upper** figure) and Case 2 (**bottom** figure) Scenario 3.

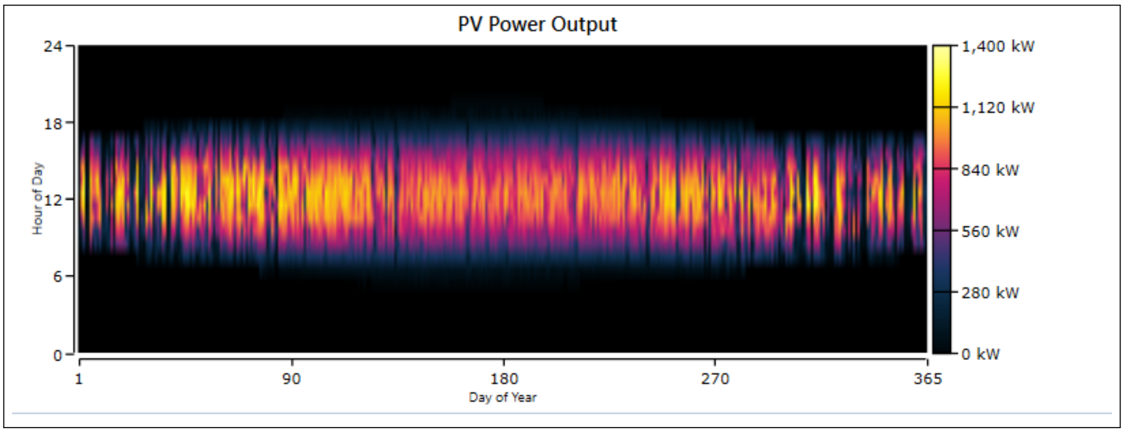

Figure 18. PV power output Case 1 and Case 2 Scenario 3.

Table 24. PV Scheme Simulation Results Case 1 and Case 2, Scenario 3.

Quantity	Value	Units
Rated capacity	1450	kW
Minimum Output	0	kW
Maximum Output	1285	kW
Mean Output	273	kW
Mean Output	6549	kWh/d
Capacity Factor	18.8	%
Total Production	2,390,365	kWh/year
PV Penetration	189	%
Hours of Operation	4386	h/year
Levelized Cost	0.0343	€/kWh

Table 25. Aeolos-H (10 kW) Scheme Simulation Results Case 1 Scenario 3.

Quantity	Value	Units
Rated capacity	70	kW
Minimum Output	0	kW
Maximum Output	96.6	kW
Mean Output	29.8	kW
Capacity Factor	42.6	%
Total Production	261,025	kWh/year
Wind Penetration	20.7	%
Hours of Operation	7374	h/year
Levelized Cost	0.0506	€/kWh

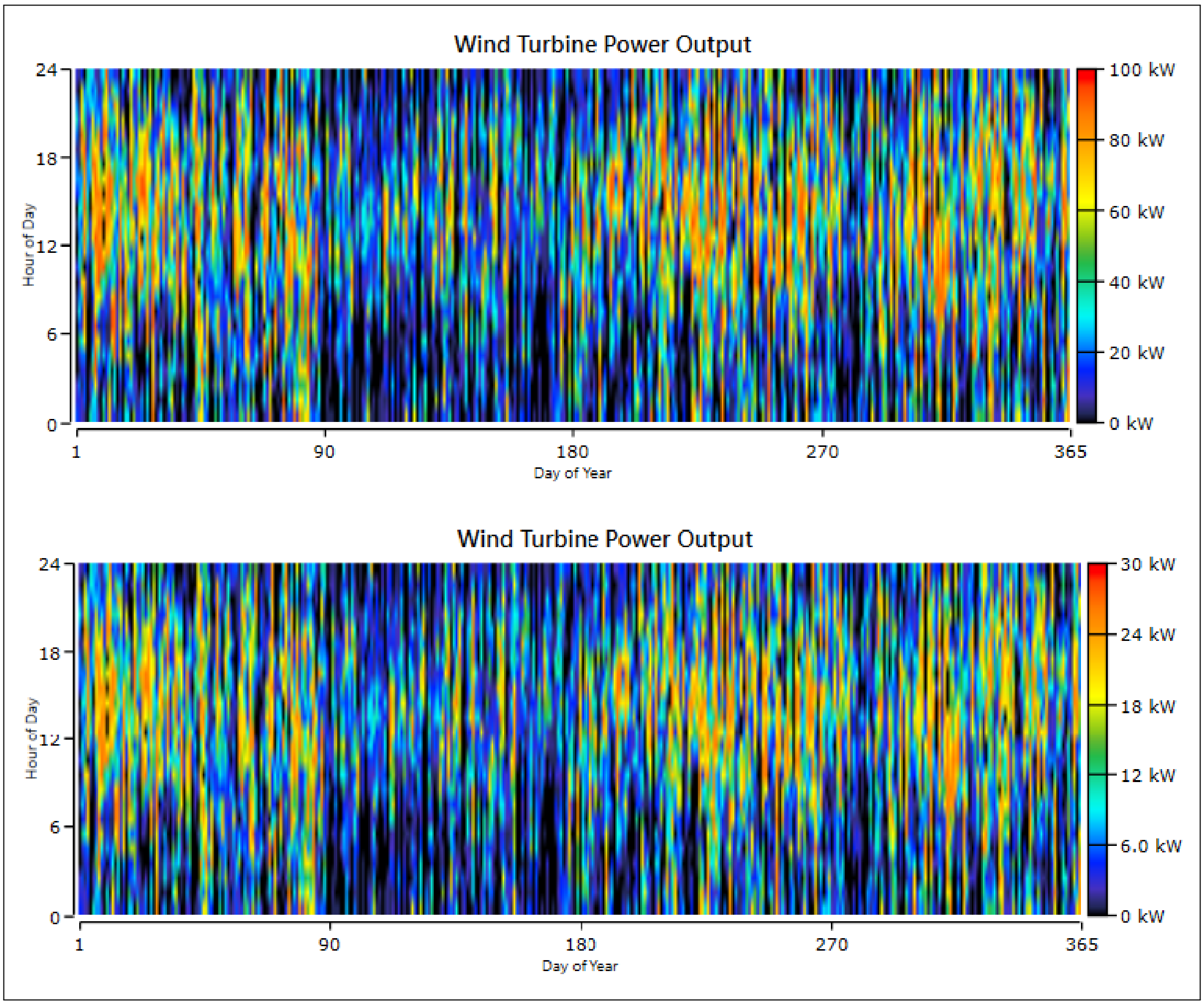

Figure 19. Wind power output Case 1 (**upper figure**) and Case2 (**bottom figure**) Scenario 3.

Table 26. Aeolos-H (10 kW) Scheme Simulation Results Case 2 Scenario 3.

Quantity	Value	Units
Rated capacity	20	kW
Minimum Output	0	kW
Maximum Output	27.6	kW
Mean Output	8.51	kW
Capacity Factor	42.6	%
Total Production	74,579	kWh/year
Wind Penetration	5.90	%
Hours of Operation	7374	h/year
Levelized Cost	0.0506	€/kWh

Another parameter for the two optimal hybrid systems for Scenario 3 is the battery. In case 1 1260 units of Hoppecke 24 OPzS 3000 and in case 2 2112 units of battery were included with days of autonomy 3 for Case 1 and 5 for Case 2. More battery units offer more autonomy, flexibility and stability. In Figure 20 State-of-Charge for each case is highlighted. Battery scheme simulation results can be seen in Tables 27 and 28. In both cases the battery units stay at medium to low levels of charge during summer months until September and are discharged to minimum (30%) during the peak load period.

Table 27. Battery Scheme Simulation Results Case 1 Scenario 3.

Quantity	Value	Units
Batteries	1260	qty
String Size	12.0	batteries
Strings in Parallel	105	strings
Bus Voltage	24.0	V
Autonomy	43.7	h
Storage Wear Cost	0.0895	€/kWh
Nominal Capacity	9008	kWh
Usable Nominal Capacity	6306	kWh
Energy In	678,208	kWh/year
Energy Out	583,614	kWh/year
Storage Depletion	383	kWh/year
Losses	94,977	kWh/year
Annual Throughput	629,327	kWh/year

Table 28. Battery Scheme Simulation Results Case 2 Scenario 3.

Quantity	Value	Units
Batteries	2112	qty
String Size	12.0	batteries
Strings in Parallel	176	strings
Bus Voltage	24.0	V
Autonomy	73.3	h
Storage Wear Cost	0.0895	€/kWh
Nominal Capacity	15,099	kWh
Usable Nominal Capacity	10,569	kWh
Energy In	783,923	kWh/year
Energy Out	674,837	kWh/year
Storage Depletion	715	kWh/year
Losses	109,801	kWh/year
Annual Throughput	727,696	kWh/year

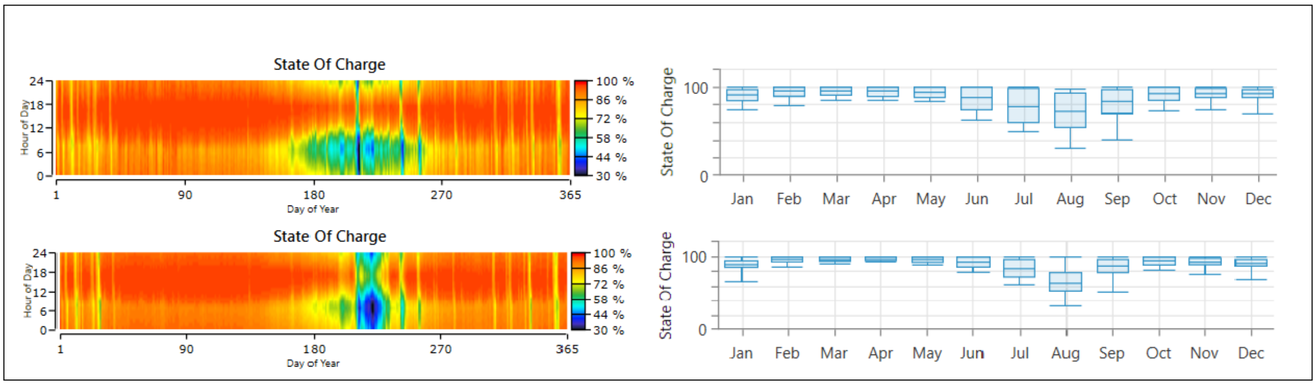

Figure 20. Battery State-of-Charge Case 1 (**upper**) and Case 2 (**bottom**) Scenario 3.

Technical difficulties are not the only obstacles that a 100% renewable hybrid system could face. Infrastructure costs are important and the implementation of high capacities of RES for the satisfaction of the load of a small island would result in high costs and expenses. First, the NPC is at 3,759,814.85 € and LCoE at 0.2241 € for case 1 while for case 2 NPC is 5,217,030.15 € and LCoE is 0.3107 €. Compared to NPC and LCoE costs of the previous scenarios case 1 of Scenario 3 has lower costs than Scenario 1 and Scenario 2. On the other hand, Case 2 is the most expensive scenario. Tables 29 and 30 summarize the financial aspects of the optimal configuration of the two study cases of Scenario 3. In both cases the main core of costs of the system is the Capital cost and then the Operating and Maintenance Cost. The Capital cost for Case 2 is clearly higher due to the greater capacity of battery. In comparison with Scenario 1 and Scenario 2 Capital Cost is much higher and this is due to the increase in capacity of RES. Operating and Maintenance costs in Scenario 3 are of a great share in the total NPC cost (1,157,673.37 € Case 1 and 1,688,118.57 €). Cash flow by cost type during the lifetime of the project for Scenario 3 are depicted in Figure 21. Additionally, battery is the most expensive component of the hybrid system for both cases. As for Case 2, where battery units is almost double than Case 1, confirm the fact that size of the battery bank is proportional to its cost. Analytical costs for the 2 cases are highlighted in Tables 31 and 32. By examining those two figures, it is confirmed that battery bank is the most expensive component having a serious effect on the NPC of the hybrid systems. Case 1 is economically advantageous with NPC of 3,759,815 €, while Case 2 with 5,217,030.15 € of NPC is not financially feasible. On the other hand, hybrid system of case 2 supports power to Donoussa's customers in a more stable way while the Excess Electricity percentage is less than in Case 1. Nevertheless, both systems provide a 100% renewable and green solution for the electrification of Donoussa island.

Table 29. Economic characteristics of the optimal configuration of Case 1 Scenario 3.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/year)
Optimal	3,759,815	0.2241	2,653,800	57,900.82	−109,559.34	1,157,673.37

Table 30. Economic characteristics of the optimal configuration of Case 2 Scenario 3.

System	NPC (€)	LCoE (€)	Capital (€)	Replacement (€)	Salvage (€)	O & M (€/year)
Optimal	5,217,030.15	0.3107	3,581,700	55,436.96	−108,225.38	1,688,118.57

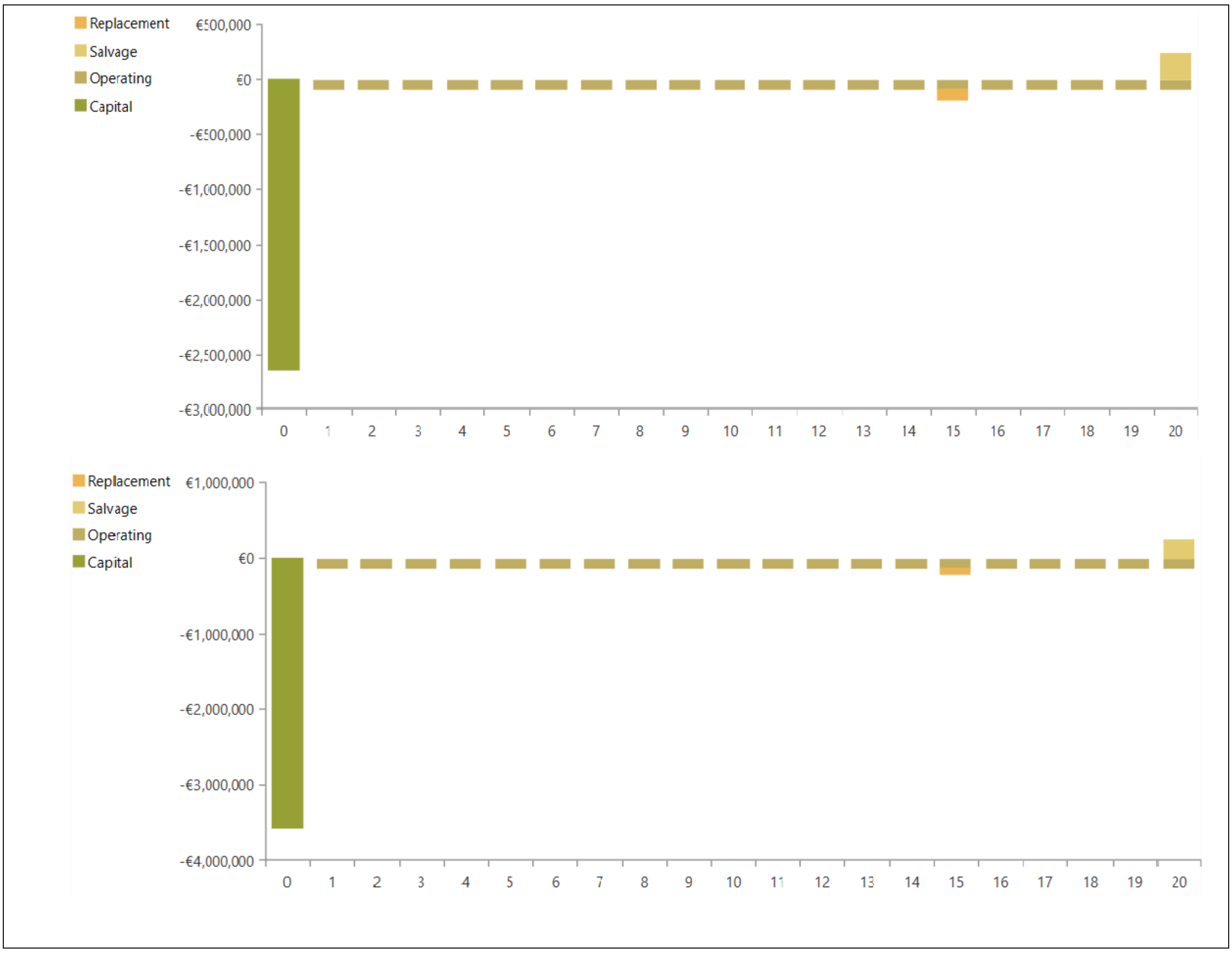

Figure 21. Cash flow summary by Cost Type Case 1 (**upper**) and Case 2 (**bottom**) Scenario 3.

Table 31. Analytical costs of each component Case 1 Scenario 3.

Component	Capital (€)	Replacement (€)	O & M (€)	Fuel (€)	Salvage (€)	Total (€)
Aeolos-H 10 kW	125,300.00	0.00	50,252.70	0.00	0.00	175,552.70
Generic Flat plate PV	899,000.00	0.00	269,875.63	0.00	−78,211.10	1,090,664.52
Generic large, free converter	117,500.00	57,900.82	0.00	0.00	−31,348.24	144,052.58
Hoppecke 24OPzS 3000	1,512,000.00	0.00	837,545.05	0.00	0.00	2,349,545.05
System	2,653,800.00	57,900.82	1,157,673.37	0.00	−109,559.34	3,759,814.85

Table 32. Analytical costs of each component Case 2 Scenario 3.

Component	Capital (€)	Replacement (€)	O & M (€)	Fuel (€)	Salvage (€)	Total (€)
Aeolos-H 10 kW	35,800.00	0.00	14,357.92	0.00	0.00	50,157.92
Generic Flat plate PV	899,000.00	0.00	269,875.63	0.00	−78,211.10	1,090,664.52
Generic large, free converter	112,500.00	55,436.96	0.00	0.00	−30,014.27	137,922.69
Hoppecke 24OPzS 3000	2,534,400.00	0.00	1,403,885.03	0.00	0.00	3,938,285.03
System	3,581,700.00	55,436.96	1,688,118.57	0.00	−108,225.38	5,217,030.15

5.4. Optimal System Configurations

The optimal system configuration of each scenario can be easily seen in the Table 33. It can be easily derived from Table 33 that configuration of Scenario 2 is the optimal result of this paper in relation to the Excess Electricity rate, the NPC and LCoE. More specifically Excess Electricity rate is 0% with a Renewable Fraction of 51%, NPC around 4.03 Millions € and LCoE almost at 0.240 €. Renewable fraction is higher than RF in Scenario 1 (20.2%) and lower than in the 2 cases of Scenario 3. The Excess Electricity rate is at 0% which is the desired percentage. NPC and LCoE of Scenario 2 are lower than Scenario 1 (4.95 Millions € and 0.295 € respectively) and Case 2 of Scenario 3 (5.22 Millions € and 0.311 € respectively). Case 1 of Scenario 3 is more economically effective than in Scenario 2. On the other hand, this system configuration faces problems due to the high percentage of the Excess Electricity rate (46.8%). Consequently, the system configuration of the hybrid system of Scenario 2 is the optimal for the satisfaction of the load of the island.

The optimal hybrid system configuration of Scenario 2 succeeds in 0% Excess Electricity rate with a 51% of renewable integration which is a satisfying percentage for Excess Electricity in comparison to [3] where Excess Energy for the 2 scenarios examined for the island of Agios Efstratios island are 37.1% and 48.1%. Moreover, in comparison to [14], the optimal system of our paper has 0% of Excess Electricity with a higher load demand. NPC cost, LCoE and Excess electricity rate of the proposed hybrid energy system of this study is better percentagewise than [30,31], our study proposes hybrid systems scenarios with a lower percentage of Excess Electricity rate. Donoussa island with a population of 167 has higher energy demands from most of the cases that were presented above and has great fluctuations in the load demand due to high tourism during the summer months.

Table 33. Optimal systems configurations of the 3 Scenarios.

Scenarios	PV (kW)	EO20 20kW (WT)	Aeolos-H 10 kW (WT)	TAD 740GE (kW)	TAD 1345GE (kW)	TAD 1345GE (kW)	D2566 ME (kW)	D2566 ME (kW)	Conv (kW)	Battery Units	Excess Elec (%)	NPC (Millions €)	COE (€)	Ren Frac (%)
Scenario 1	100	2	-	200	250	250	80	80	80	-	6.68	4.95	0.295	20.2
Scenario 2	260	2	2	200	250	-	80	-	200	420	0	4.03	0.240	51.0
Scenario 3 Case 1	1450	2	2	-	-	-	-	-	470	1260	46.8	3.76	0.224	100
Scenario 3 Case 1	1450	-	2	-	-	-	-	-	470	2112	41.8	5.22	0.311	100

6. Conclusions

In this work we explored the possibility of the operation of a hybrid renewable energy system in Donoussa island which could supply the consumers reliably and would lower the dependence from the conventional power units and fossil fuels on the island. Three main scenarios were implemented with different renewable adoption rate (20%, 50% and 100%). Gradually, conventional units of the existing power system were reduced in each scenario. Several techno-economical analyses were performed with the help of the HOMER software. The optimal hybrid system for each scenario was chosen with minimum Excess Electricity percentage and the optimized NPC and LCoE as criteria. The main principle of the study was the continuous satisfaction of load demand and the investigation for a technically and economically feasible solution with a hybrid system for a lifetime of 20 years. The Optimal system scenario was the hybrid system proposed for Scenario 2 with 0% of Excess Electricity and NPC at 4,031,102.03 € and LCoE at 0.2401 €. Similar results, percentagewise, are observed in other studies [3,14,30,31]. The investigation that was conducted here could be used as a basis for future work. For instance an interconnection of the Donoussa island power system to the mainland electrical grid could further increase the reliability of the system, while lowering the cost of electricity on that remote island and this is a scenario worth exploring further.

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